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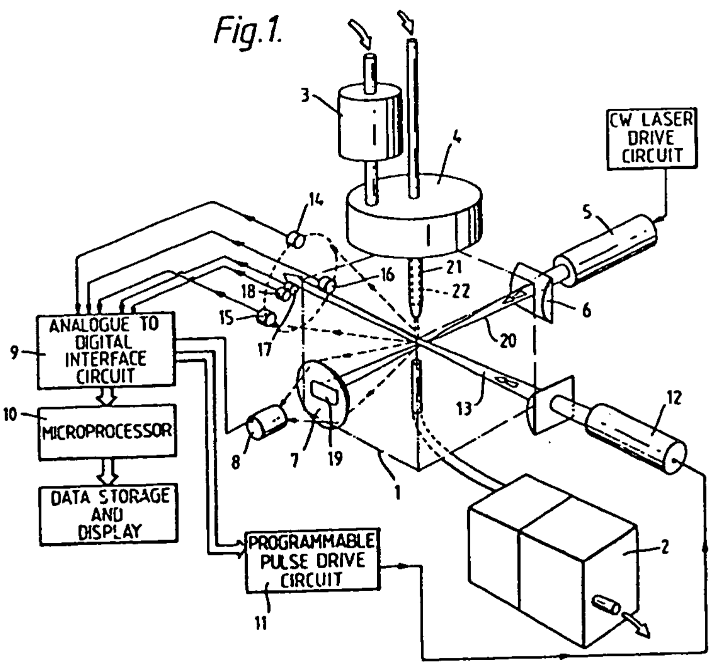
G1A
Selected US specifications from IPC sub-class G01N

(54) Analyser for airborne particles

(57) An apparatus for detecting the size and shape of particles in a sampled airstream, e.g. for pollution monitoring, includes a continuous-wave diode laser (5) and a pulsed laser diode (12) at right angles to one another. A stream of air is passed through a beam (20) from the continuous-wave diode laser (5). Any particle detected by the beam (20) results in a signal to a detector (8). The signal is analysed to obtain the size of the particle and the pulsed laser diode (12) is caused to operate, at an intensity inversely proportional to the size of the particle, so as to intercept the particle again. The particle is tested for sphericity by detectors (14), (15), (16) and size by detectors (17), (18). The apparatus can count individual particles at rates of e.g. 20,000 per second, while distinguishing between spherical and non-spherical particles.

Fig.1.



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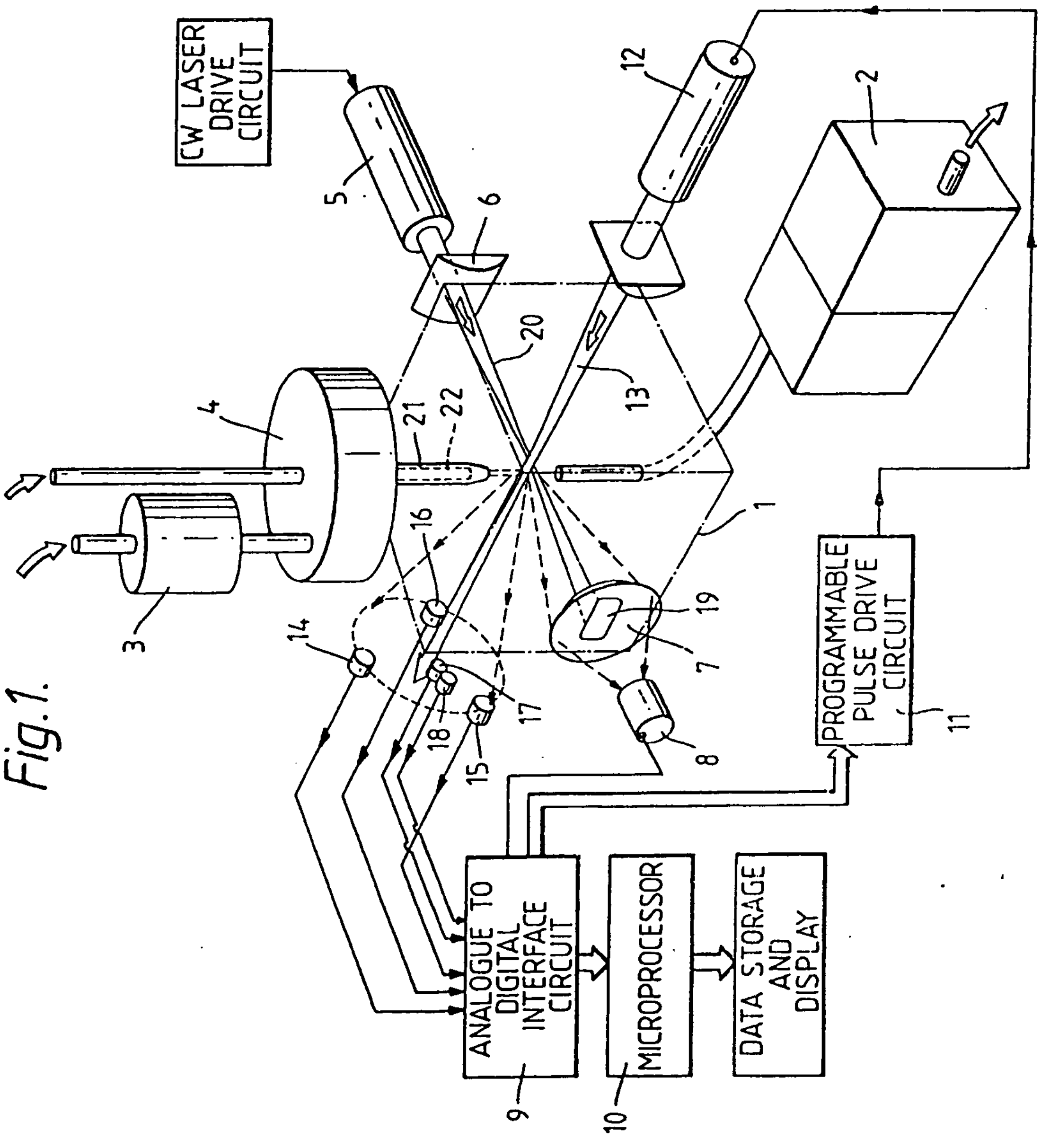
The drawing(s) originally filed was/were informal and the print here reproduced is taken from a later filed formal copy.


CW LASER DRIVE CIRCUIT
PROGRAMMABLE PULSE DRIVE CIRCUIT
ANALOGUE TO DIGITAL INTERFACE CIRCUIT
MICROPROCESSOR
DATA STORAGE AND DISPLAY
1
2
3
4
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21
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Fig.1.

Fig. 2.

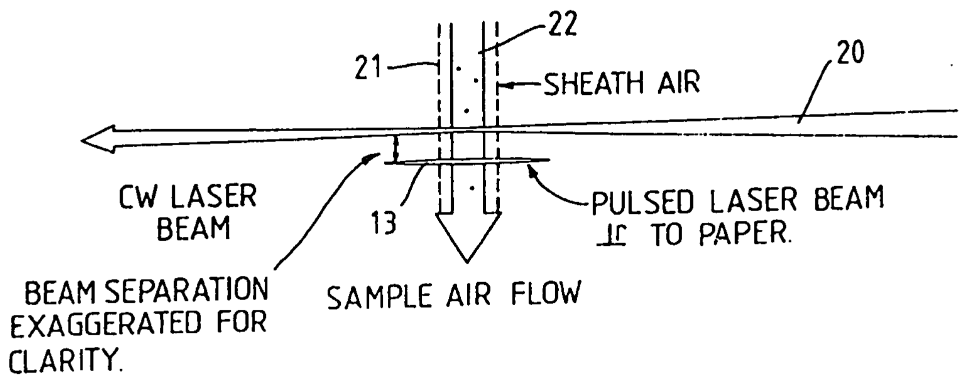

22
21
20
SHEATH AIR
CW LASER BEAM
13
PULSED LASER BEAM ⊥r TO PAPER.
BEAM SEPARATION EXAGGERATED FOR CLARITY.
SAMPLE AIR FLOW

Fig. 3.

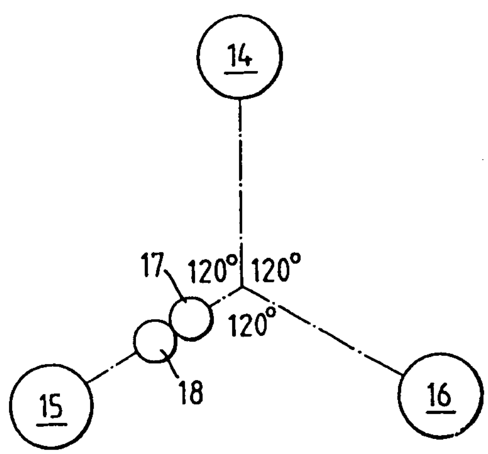
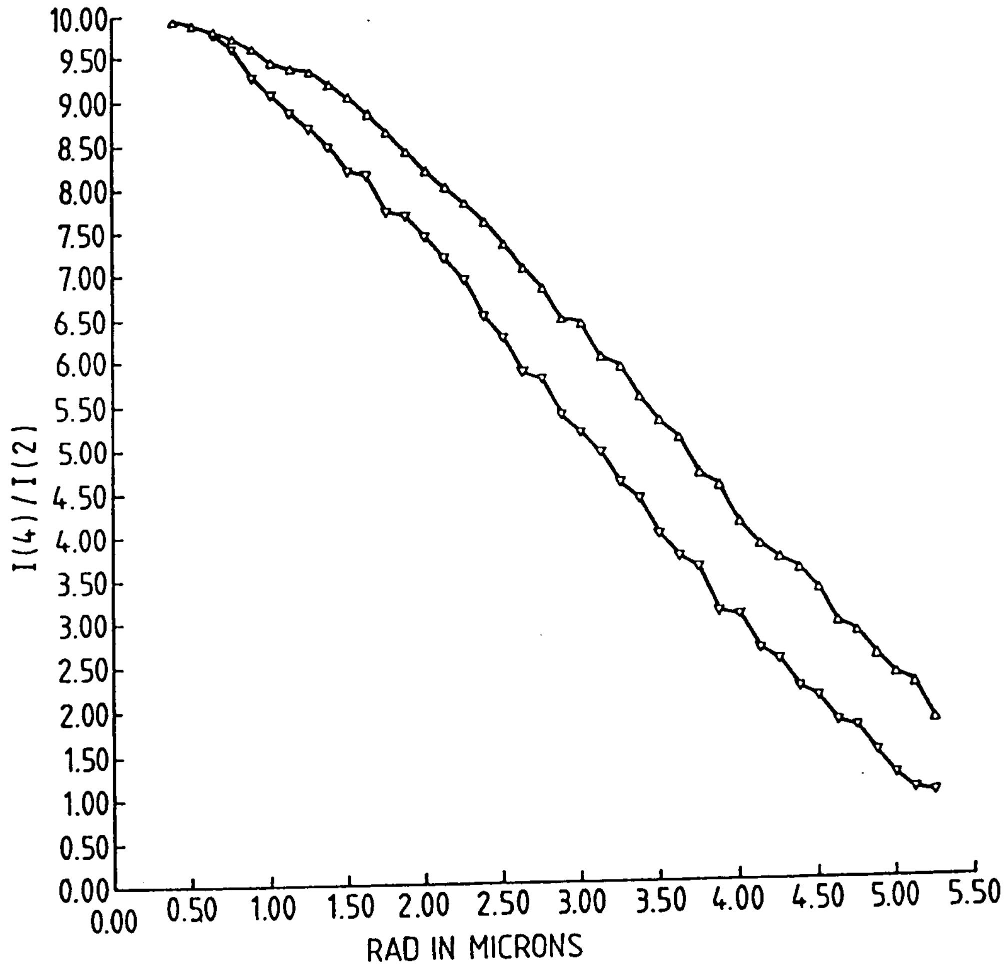

14
17
120°
120°
120°
18
15
16

Fig. 4.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RAD IN MICRONS

SPECIFICATION

Analyser for airborne particles

This invention relates to apparatus for the analysis of airborne particles. In the study of aerosols, aerosol dispersion and airborne particulate pollution control, for example, there is a requirement for the rapid determination of particle size distribution especially in the diameter range 1 to 10 microns, together with some knowledge of the geometry and symmetry of individual particles. The latter information could, for example, enable particles with spherical symmetry to be identified and thus allow the counting/monitoring of liquid droplets in an environment including other solid, non-spherical particles.

It is desirable for such apparatus to be able to count individual particles in a sample at rates of, typically, 20,000 particles per second, to be able to distingush between spherical and non-spherical particles in the sample and to count each type. Another desirable feature is to categorise spherical particles having diameters of a few microns into a number of size bands and also in this connection to classify particle coincidences as 'non-spherical' and hence to ignore them in the compilation of size spectra.

The normal techniques for the examination of particles, as used in several instruments available commercially, employ the detection and analysis of electromagnetic radiation scattered by the particles. All such instruments use a mechanical mechanism to drive the sample air through a "sensing volume" where the carried particles are illuminated by the incident electromagnetic radiation. The radiation scattered by the particles is received by one or more detectors which convert the energy to electrical signals from which information may be extracted by appropriate electrical circuits.

One class of instrument available commercially permits the collection of scattered radiation from large numbers of particles simultaneously, and uses this information to determine a mean figure for particulate mass per unit volume of gas or air, or the statistically averaged size distribution of particulate matter. These instruments are not capable of examining individual particles, and therefore cannot yield accurate particle counts or information relating to particle morphology.

A second class of instrument uses the properties of laminar flow in gases to restrict the particles to a smaller sensing volume and then, by focusing the incident electromagnetic radiation in some way, is capable of the examination of individual particles, yielding a particle count and possibly approximate size distribution. No available instrument of this type is able to distinguish between spherical and non-spherical particles.

The majority of the instruments just referred to employ a helium-neon laser as the source of illumination, so that, as a consequence, the instruments are not readily portable because of their fragility and the combined size of the instrument and its associated power supply.

Instruments employing a diode laser would not suffer from these disadvantages, being small, robust and having a low power consumption. On the other hand, because of the need to restrict heat generation in their small volume, their power output in continuous-wave mode is too low to be sufficient, even when the beam is focused, to generate a scattered light signal which produces large enough signal-to-noise ratio for accurate determination of micron-sized particle characteristics. In pulsed mode with a duty cycle of 10%, for example, the power output may be increased by about an order of magnitude; but this would still be insufficient to operate a particle analyser in the manner employed hitherto.

The power output from a single diode laser might be sufficient to determine the size and shape of the larger particles under investigation, but since the scattered intensity of light from an illuminated particle is dependent on at least the fourth power of its diameter, a signal-to-noise ratio approaching 100,000:1 throughout the range would be needed to determine the size and shape of particles to a useful accuracy even in the size range of $1\mu m$ to $10\mu m$. Such a ratio would place unacceptably stringent demands on the performance and properties of the electronic circuitry, giving rise to excessive expense and care required over the conditions under which the instrument could be used.

On account of these problems, it is proposed to use two diode lasers in tandem, and this invention therefore consists of apparatus for the analysis of airborne particle streams comprising a first laser adapted to operate continuously, a presence detector for producing an electrical output proportional to the scattered light received when a particle passes through the beam of the first laser, a converter driven by the output of the presence detector to produce a drive pulse for a second laser, the drive pulse being an inverse function of the output from the presence detector and causing the second laser to illuminate the said particle with a beam intensity proportional to the drive pulse, and a size detector for receiving light from the second laser scattered by the said particle.

By this means, the first laser is employed essentially in the detection of the presence of particle within its beam, and since the output from the presence detector need only be an approximate function of the size of the particle, a high power output from the first laser is not required. Moreover, the second laser operates only in the presence of a particle, ie,

when there is an output from the presence detector, and if the convertor produces a drive pulse for the second laser which varies inversely with the output from the presence detector then the output from the second laser will result in an output from the size detector which is a lower order function of the size of the particle. The signal-to-noise ratio required for the useful size determination of particles throughout the size range is thus greatly reduced.

The size detector may conveniently comprise two detectors disposed radially from the beam of the second laser at two known scattering angles, means for comparing the scattered intensity received at each detector, and means for converting the ratio of intensities thus measured into particle size by the application of a pre-determined formula.

In another aspect of the invention there is provided means for discriminating between spherical and non-spherical particles, such discrimination enabling particles determined to be non-spherical to be discarded from any size analysis of particles and for particle coincidences to be classified as 'non-spherical' and thus to prevent them giving misleading results.

Such means may comprise three or more detectors disposed around and at the same scattering angle of the beam of the second laser, means for comparing the scattered light received at each detector from an illuminated particle, and means for classifying as non-spherical any particle which causes a variation in scattered intensity between the detectors of more than a specified proportion. The scattered proportion may be between 2% and 5%.

There may conveniently be three symmetrically disposed detectors provided for this purpose, one of which may, without signficant loss of accuracy, be one of the size detectors.

By way of example, one embodiment will now be described with reference to the drawings, of which

Figure 1 is a schematic perspective diagram of a portable airborne particle analyser constructed in accordance with the invention,

Figure 2 is a schematic diagram showing more clearly the spatial relationship between the beams from the first and second lasers,

Figure 3 is a schematic diagram in a plane normal to the beam from the second laser showing the spatial relationship of the size and sphericity detectors, and

Figure 4 is a graph showing as an example the intensity ratio of scattered light received by detectors set at 2° and 4° from the illuminating beam for particles having two extreme refractive indices at a wavelength of $0.55\mu m$.

With reference to Figure 1, an air sample containing particles, such as aerosols, whose size spectrum is to be determined, is drawn through the scattering chamber 1 of the analyser by means of a constant volume sampling pump 2. A portion of the air sample is passed through a filter 3 to remove particulate matter, and this air then forms a sheath which surrounds and confines the sample containing particles in a laminar flow unit 4. This unit causes the particles to be restricted to a cyclindrical column typically of 1 mm diameter and travelling with a velocity of 10 m/s. Particles thus carried into the scattering chamber 1 intersect normally with a focused beam from a continuous-wave diode laser 5.

The dimensions of the beam from this laser in the focal plane where the beam intersects the particle flow are typically 30 microns vertically by 5 mm horizontally (as indicated in Figure 2), and the focal length of the focusing lens 6 is such that the Rayleigh range at the focus is typically 2 mm in length, ie sufficient to encompass the air-flow column diameter and thus to ensure equal illumination for all particles regardless of their lateral position within the column. This beam profile in combination with a typical sample flow-rate is such that, for particle concentrations of up to approximately 2.5 × 10 particles per cubic metre, particle coincidences in the beam are negligible.

Radiation scattered by each particle as it traverses the beam is collected by a receiving lens 7 and is focused onto a detector 8. The unscattered beam is absorbed by a beam stop. The detector 8 is typically of the PIN-diode type, possibly with an integral amplifier. An analogue-to-digital interface circuit 9 then detects the magnitude of the signal pulse from the detector 8 and converts this value to a digital binary form, typically with 8-bits resolution. This process may be performed by a Peak-Hold integrated circuit device in conjunction with an analogue-to-digital integrated circuit device, using a threshold detector to provide the correct synchrony with the particle transition through the beam.

The magnitude (in binary form) of the signal pulse is transferred to a microprocessor 10 and to a programmable pulse-drive circuit 11. The latter uses the magnitude information to control the power with which a pulsed diode laser 12 emits a pulse of electromagnetic radiation. The power of the pulse is inversely proportional to the magnitude of the signal-pulse derived from the laser 5 such that a small particle results in a higher-power pulse than does a larger particle. As mentioned above, this arrangement enables the intensity of light scattered from the particle whilst in the pulsed beam to be, to a first order approximation, independent of particle size. As a result, in addition to the benefits of dynamic range compression, the detectors collecting this scattered radiation can be designed to have a responsivity which fully utilises the range of the subsequent analogue-to-digital converters, thus minimising quantisation errors.

The firing of the pulsed laser 12 is con-

trolled electronically using a knowledge of the particle flow velocity and is such that the particle will have reached the path of the pulsed beam at the time of firing. The pulsed beam 13 is therefore marginally below the continuous wavebeam 14 (see Figure 2). Typically the separation of the two beams is of the order of 100 microns.

The light scattered by a particle in the pulsed beam is received by three sphericity detectors 14, 15 and 16 disposed symmetrically around the axis of the beam as shown more clearly in Figure 3. The detectors may for example be discrete PIN-diodes, or optical-fibre light guides which convey the light to PIN-diodes remote from the scattering chamber 1. The symmetrical disposition of the detectors is such that spherical particles will scatter light from the unpolarised pulsed laser equally to all three, whereas different scattered intensities will in general be received from non-spherical particles.

In cases where the output of the pulsed laser is linearly polarised, scattering from spherical particles will not be exactly symmetrical, and it will be necessary to insert a quarter-wave plate in the path of the beam before the scattering chamber so as to convert the polarization to the circular form which will yield symmetry of scattering.

The outputs of the sphericity detectors 14, 15 and 16 are digitised via analogue-to-digital converters typically to 8-bit resolution, and, as mentioned, since the signals resulting from different sized particles are of the same order of magnitude, the responses of the detectors may be adjusted to utilise fully the range of the analogue-to-digital coverters so that quantisation errors caused by digitisation are minimised and rendered insignificant even with 8-bit resolution. The digital signals are fed to the microprocessor 10 which first corrects them for systematic errors caused, for example, by differences in detector responsivity. It then compares the magnitudes of the three signals and if any one signal differs from the mean of the three by more than a prespecified percentage, the particle is recorded as non-spherical. The specified percentage is typically between 5% and 2%.

Size detectors 17 and 18, disposed to detect radiation scattered from a particle at two different angles from the beam, typically 2° and 4° respectively, are used to provide a measure of the diameter of those particles which are considered spherical. To achieve this the outputs of the size detectors are digitized and delivered to the microprocessor 10 where their magnitudes are compared. The ratio of the two signals may be used to infer a particle diameter, and this result may be rendered unambiguous by an additional cross-check provided by the already stored digital value of the pulse generated by the particle transit through the beam from the continuous-wave laser 5.

The microprocessor 10 stores a cumulative count of nonspherical particles and spherical particles together with a cumulative count of the number of spherical particles in each of a specified number of size intervals (typically 5 to 10) in the range 1 to 10 microns diameter. Additionally, because particle coincidences in the beam will almost always produce asymmetric scattering, they are registered as non-spherical particles and do not contribute to the compilation of a size spectrum. This removes one of the sources of error present in other instruments designed to determine particle size distributions which generally classify particle coincidences as single large particles.

On request the following data may be displayed:

total count-rate/second
spherical count-rate/second
total particle count
total spherical particle count
spherical particle count in specified size interval
a histogram of spherical particle size versus frequency.

The basis for the conversion of the intensity ratios measured by the size detectors to a particle diameter can be summarised as follows:

For scattering angles θ for which $\sin\theta < 0.61\,\lambda a_{max}^{-1}$, where $\theta < 6°$ for particles up to $10\mu m$ diameter, the intensity of scattered light $J(n,a/\lambda,\theta)$ varies approximately as a^4 but is only slightly dependent on n, where

λ is the wavelength of the laser radiation,
a is the particle diameter, and
n is the refractive index of the particle.

The ratio R between the intensities received by two small detectors at two angles θ_1 and θ_2 from the beam can be expressed therefore as

$$R(n,a/\lambda) = \frac{J(n,a/\lambda,\theta_2)\,\Delta\omega_2}{J(n,a/\lambda,\theta_1)\,\Delta\omega_1}$$

where ω_1 and ω_2 are the solid angle embraced by the respective detectors.

In principle, θ_1 and θ_2 can be chosen so as to optimise the variation of the ratio R with radius and reduce its dependence on refractive index. R generally decreases with radius for all refractive indices. Two composite curves of the extreme values of R for all the refractive indices at each particle radius may be obtained and used to calibrate the instrument. This calibration will also include the error in the size determination of a particle of unknown refractive index. An example of such curves for the loci of R for detectors at 2° and 4° is shown in figure 4. This particular configuration is typical of that which may be employed in this instrument.

The size classification is carried out by using an algorithm which relies on a look-up table derived from the calibration curves. When stored in the microprocessor such a program will allow the rapid classification of a particle from the experimental values of R.

For values of θ larger than those for which the above considerations apply, for example in the forward range of 10° to 80°, it is found that the scattered intensity J exhibits oscillatory behaviour with θ. Nevertheless, a detector which collects light over a moderate solid angle ω will give an output proportional to $\int(n,a/\lambda,\theta)$ which varies approximately as a^2. A typical solid angle is that included within a cone of semiangle 20° about the mean angle of the detector.

In principle therefore it is possible to employ a small area detector for which θ is small and an integrating detector for scattering at large angles and thus obtain a size measure

$$S(n,a/\lambda) = \frac{J(n,a/\lambda,\theta_1)\Delta\omega_1}{\int J(n,a/\lambda,\theta)d\omega}$$

Although the size measure S is not as useful as R it is still of interest since it permits the implementation of a more refined particle sizing procedure which uses both R and S as experimental input parameters. Moreover, the integrating detector could be one of the sphericity detectors, thus simplifying the instrument design.

The present instrument does not require experimental calibration with sets of particles of known distributions. However, it is important for the accurate operation of the system that the responsivities and voltage off-sets of the separate detector channels are known. Digital correction of the signals can then be introduced if this is required.

CLAIMS

1. Apparatus for the analysis of airborne particle streams comprising a first laser adapted to operate continuously, a presence detector for producing an electrical output proportional to the scattered light received when a particle passes through the beam of the first laser, a converter driven by the output of the presence detector to produce a drive pulse for a second laser, the drive pulse being an inverse function of the output from the presence detector and causing the second laser to illuminate the said particle with a beam intensity proportional to the drive pulse, and a size detector for receiving light from the second laser scattered by the said particle.

2. Apparatus according to Claim 1 in which the size detector comprises two detectors disposed radially from the beam of the second laser at two known scattering angles, means for comparing the scattered intensity received at each detector, and means for converting the ratio of intensities thus measured into particle size by the application of a pre-determined formula.

3. Apparatus according to either preceding claim including means for discriminating between spherical and non-spherical particles, said means comprising three or more detectors disposed around and at the same scattering angle of the beam of the second laser, means for comparing the scattered light received at each detector from an illuminated particle, and means for classifying as non-spherical any particle which causes a variation in scattered intensity between the detectors of more than a specified proportion.

4. Apparatus according to Claim 3 in which the means for discriminating between spherical and non-spherical particles comprise three detectors symmetrically disposed about the beam of the second laser.

5. Apparatus according to either Claim 3 or Claim 4 in which one of the detectors is also a size detector.

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